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Seasonal Performance Analysis Of a Residential Heat Pump Using Different Fluids With Low Environmental Impact

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Abstract

The growing of the energy consumption, in particular from buildings, both residential and commercial has induced a major interest for the analysis of the seasonal performance of heat pumps. The same considerations are effective for the well-known environmental problems related to direct and indirect emissions of carbon dioxide into the atmosphere and the incentives to support energy efficiency. In this work an air to water heat pump working with R290 and HFO1234yf has been modeled and simulated using the software package IMST-ART in order to evaluate the seasonal performance. Two different types of applications were considered: fan coils and radiant heat floor panels. Different types of building are considered. The seasonal performance in heating mode, SCOP, is calculated by coupling the performance of the heat pump in different operative conditions to a heating demand curve, in two different climate zones (average and colder). The results of the simulations show better performance of the heat pump with propane in both climates and applications, which is probably due to the state of current technology of the different components. In particular, the global performance of the compressor working with R1234yf is not yet optimized. At the same time a new design of the evaporator is desirable to reduce the pressure drops with R1234yf.

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Keywords: Heat pump ; HFC replacement; Propane, R1234yf; Performance analysis; SCOP

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1. Introduction

As reported by the IEA (International Energy Agency) [1], in 2040the global energy demand is expected to increase by 37% and carbon dioxide (CO_2) emissions will increase by 20%, with an raise in long-term global average temperature of 3.6 °C. In addition, as illustrated in Annual Energy Outlook 2015 [2], the increase in the cost of energy by 18% by 2040 has led to improve and develop more efficient systems from the energy point of view. In particular, the building sector, both residential and commercial, is the largest energy consuming sector in the world. Specifically, it accounts for more than one-third of total final energy consumption and in like manner source of carbon dioxide emissions [3]. In order to reduce the energy consumption by end uses for space heating and cooling, heat pumps represent a valiant economic alternative for heat recovery from different sources in several applications, such as industrial, commercial and residential fields. Moreover, heat pumps are considered as technologies that use renewable energy [4].As regards the environmental problem, instead, it is necessary to investigate the use of alternative fluids characterized by low values of global warming potential(GWP) and high performances. In this context the manufacturers focus their research on the choice of appropriate working fluids and performance evaluation. The European Union, indeed, has already approved several regulations concerning the cognizant use of refrigerant gases usually used (HFC) and planned a gradual removal of fluids characterized by high values of GWP in the next years [5]. In this regard, we are witnessing the replacement of traditional HFC refrigerants with new fluids, having zero ozone depletion potential(ODP) and low GWP, such as hydrofluoroolefins (HFO) R1234yf and R1234ze, or natural fluids such as propane (R290) and carbon dioxide (R744).On the other hand, it is important to evaluate the performance not only in the nominal point but also in different possible operating conditions. The seasonal performance of heat pumps in fact is closely related to the external boundary conditions, such as the ambient temperature and the intended use, extremely variable during the operating period [6].As shown by the analysis of Sarbu [7] there are different possibilities to replace the traditional refrigerants. Concerning the use of HFO mixture or natural fluids in heat pumps system for residential applications, the adoption of R1234yf and propane (R290) has been proposed in different works by Ghoubali et al. [8], Babiloni [9] and Palm [10].As demonstrated in this work, the alternative fluids abovementioned do not necessarily lead to performances similar to traditional ones. Another aspect to consider is the technological progress achieved by the components of the system, working with different fluids. In this context, numerical simulations through development of accurate models allow to characterize the performance of any machine by changing working fluids, type of application and/or reference climate. In the present work, the seasonal performance of two air-to-water residential heat pumps working with propane and R1234yf are investigated for different reference climates and different final applications.

2. Characteristics of the two heat pumps

This paper presents the simulations' results of an air-to-water heat pump working with propane and HFO1234yf. The layout consists in a scroll compressor, a plate heat exchanger as condenser, a liquid receiver, a finned coil as evaporator, and an expansion valve.

The geometric characteristics of the compressor and two heat exchangers have been modified in order to obtain the same heating capacity and the same mean $\overline{\Delta T}$ in the heat exchangers, at nominal conditions. The heat pumps are modeled in the vapor compression software package IMST-ART. Using IMST-ART, the heat pump model was designed considering the information of the catalogue data provided by the component manufacturers. IMST-ART software has been experimentally validated in several studies [11], [12],[13].

Its nominal heating capacity is of 32.8 kW when heating water from 40 to 45°C at the condenser (fan coil) and working with air entering the evaporator at 2°C, while when heating water from 30 to 35°C at the condenser (radiant heat floor panels) and the same condition of air at the evaporator, the nominal heating capacity is 34.3 kW. Tables 1, 2, 3 report its main characteristics.

Table 1. Compressor characteristics.

COMPRESSOR	Units	Propane	R1234yf
Compressor Type		Scroll	Scroll
Displacement	cm^3	227.6	526.6
Speed	rpm	2900	1450

Table 2. Condenser characteristics.

		FAN COIL		PANN RAD	
CONDENSER	**Units**	**Propane**	**R1234yf**	**Propane**	**R1234yf**
Type		Plates	Plates	Plates	Plates
H	m	0.47	0.43	0.47	0.41
# plates		80	78	80	76
Qco	kW	32.79	32.85	34.16	34.45
UA	$kW\cdot K^{-1}$	5.24	5.24	5.40	5.47
ΔT	K	6.33	6.33	6.38	6.35
U	$kW\cdot K^{-1}\cdot m^{-2}$	1.32	1.48	1.36	1.67
A	m^2	3.96	3.54	3.96	3.27

Table 3. Evaporator characteristics.

		FAN COIL		PANN RAD	
EVAPORATOR	**Units**	**Propane**	**R1234yf**	**Propane**	**R1234yf**
Type		Finned-tube	Finned-tube	Finned-tube	Finned-tube
L	m	2.4	2.3	2.4	2.5
Qev	kW	23.68	22.36	26.38	25.98
UA	$kW\cdot K^{-1}$	17.53	17.01	17.17	17.40
ΔTml	K	1.35	1.32	1.54	1.49
U	$kW\cdot K^{-1}\cdot m^{-2}$	0.13	0.14	0.13	0.13
A	m^2	131.12	125.65	131.12	136.58

Table 4 shows the main properties of the two working fluids chosen

Table 4. Main properties of the two working fluids: R290 and R1234yf.

	T_c [°C]	ρ_l[kg·m^{-3}] @ 2 °C	ρ_{vs}[kg·m^{-3}] @ 2 °C	Δh_{ev} [kJ·kg^{-1}] @ 2 °C	c_l [kJ·kg^{-1}·K^{-1}]	ODP	GWP	Flammability	Toxicity
R290	96.74	525.88	10.975	372.04	2.51	0	3	3	A
R1234yf	94.7	1288.1	15.465	197.08	1.35	0	4	2L	A

2.1 *Performance maps*

The performance maps obtained by simulations are shown in Fig. 1-2:

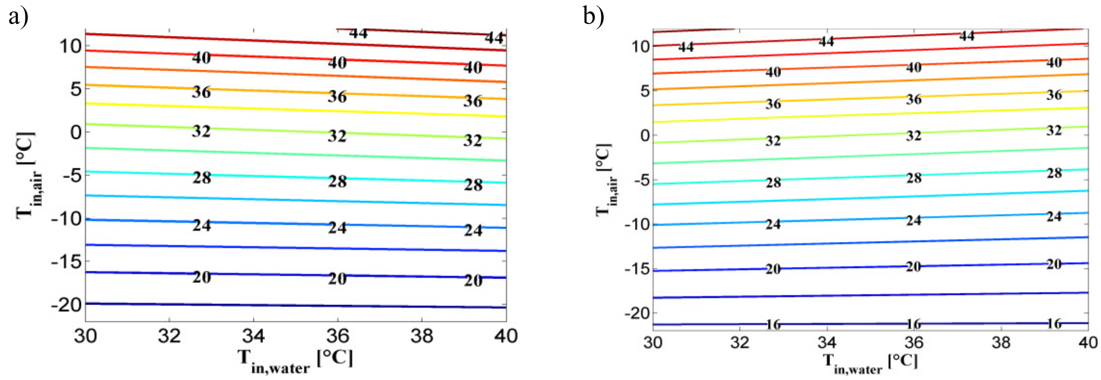


Fig. 1. Performance maps of the heat pump in terms of heating capacity (propane (a), R1234yf (b)), as a function of the inlet temperatures of water at the condenser and the inlet temperatures of air at the evaporator.

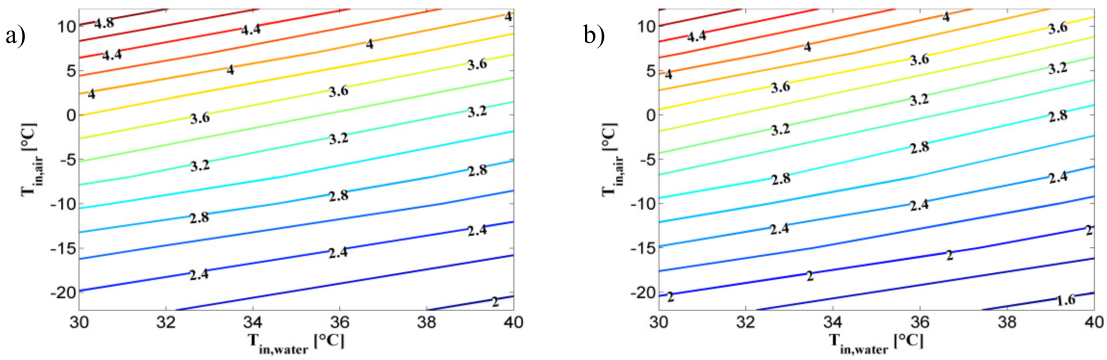


Fig. 2. Performance maps of the heat pump in terms of COP (propane (a), R1234yf (b)), as a function of the inlet temperatures of water at the condenser and the inlet temperatures of air at the evaporator.

The thermal capacity of the two heat pumps is almost the same for all operating conditions while the COP of the propane heat pump is greater than that working with R1234yf. This difference is due to the lower performance of the compressor, with an enhancement of the heat pump with R1234yf at high temperatures thanks to a greater value of the global efficiency of the compressor, the major intrinsic losses pertaining the throttling phase and the highest evaporator pressure drops.

The Fig.3-4 show the T-s thermodynamic cycles of Propane and R1234yf at nominal condition, taken from the IMST-ART simulations.

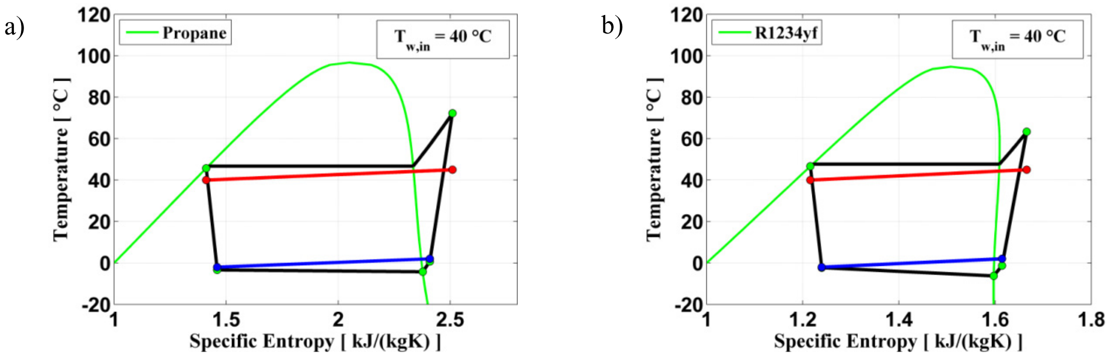


Fig. 3.T-s thermodynamic cycles of Propane (a) and R1234yf (b) at nominal condition (Ambient T = 2 °C, T water inlet cond = 40 °C, T water outlet cond = 45 °C). Fan coil case.

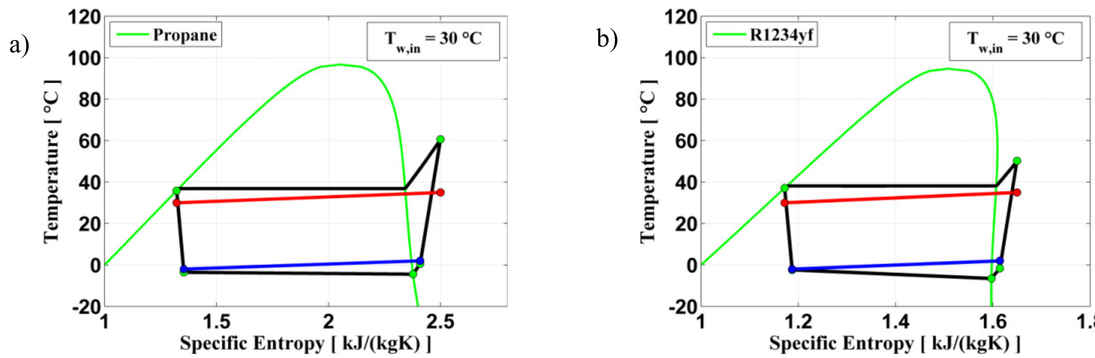


Fig. 4.T-s thermodynamic cycles of Propane (a) and R1234yf (b) at nominal condition (Ambient T = 2 °C, T water inlet cond = 30 °C, T water outlet cond = 35 °C). Radiant heat floor panels case.

T-s thermodynamic cycles underline that at nominal condition the evaporator pressure drops are greater in the heat pump working with R1234yf. On the contrary, the propane heat pump is characterized by a higher temperature at the outlet of the compressor and therefore a higher irreversibility related to desuperheating. Analyzing the simulations data it is possible to highlight that the R1234yf heat pump shows a greater number of operating conditions at high values of the pressure ratio with lower values of the global efficiency of the compressor. This involves higher electrical consumption by the compressor and lower performance of the R1234yf heat pump in different operating conditions. In the overall operative range, the HFO1234yf heat pump shows a higher vapor quality at the evaporator inlet. This leads to major intrinsic losses pertaining the throttling phase and lower COP. Moreover, a lower COP of the heat pump working with R1234yf is also due to a higher evaporator pressure drop.

3. Seasonal performance analysis

Seasonal performance of heat pumps is closely related to the external boundary conditions, such as the ambient temperature and the intended use. The European Standard UNI EN 14825-2013 provides calculations method to evaluate the seasonal coefficient of performance SCOP. This standard specifies the external boundary conditions: the air dry bulb temperature at the inlet of outdoor heat exchanger and the temperature of the water at the inlet/outlet of the internal heat exchanger.

The operating conditions simulated to characterize the performance of the two heat pumps are reported in the UNI EN 14825-2013.

To calculate the seasonal performance, a climate zones and a heating demand curve have to be defined. In this work two different climate zones have been considered: the Average, correspondingto Strasbourg, and the colder, correspondingwithHelsinki. For eachreferenceclimate thestandard reportsthe numberof hours for eachambient temperature.The heating demand is obtained from the European project ENTRANZE [14] for three different types of building: apartment block, office and school.

In order to give additional information on equivalent m^2 of the buildings considered, for which the considered heat pumps are able to fulfill the heating demand, the bivalent temperature is chosen equal to 2 °C for the average reference climate and -7 °C for the colder referenceclimate.These values are the maximum suggested by the Standard. In support of this, as shown in the article by Naldi et al. [15], considering a temperate climate, the SCOP of an on-off heat pumpis approximatelyconstantvaryingthe bivalent temperature in the range -2÷ 2 °C.

The equivalent m^2 of the buildings considered are reported in Table 5.

Table 5. Equivalent m^2 of the buildings considered.

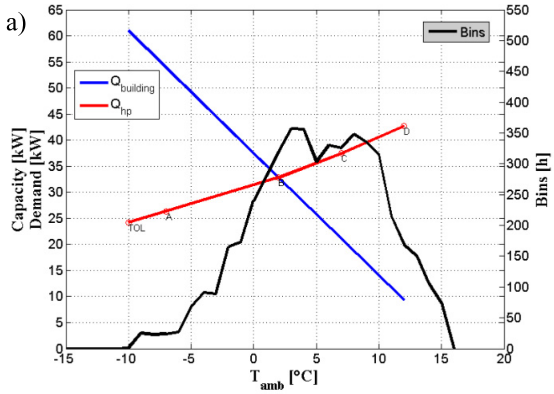
Equivalent m^2	APARTMENT BLOCK	OFFICE	SCHOOL	
Paris	862	752	691	FAN COIL
Helsinki	767	430	464	
Paris	901	786	722	RAD PAN
Helsinki	799	448	483	

The seasonal performance of the two heat pumps, by varying the final user (fan coil or radiant heat floor panels) and the reference climate (Strasbourg and Helsinki), are evaluated following the procedure reported in UNI EN 14825.

Next figure illustrates the heating capacity and heating demand with the bin hours for the fan coils case, considering the average climate.

The values of $SCOP_{on}$ and $SCOP_{net}$ are reported in Table 6.

Considering the fan coil case, the seasonal performance of the heat pump working with R1234yfispenalized because of the worse COP values. As shown previously, this is due to a greater compression ratio when room temperature drops below 2°C and therefore a lower global efficiency of the compressor. In the case of using radiant floor panels, however, the difference between the two heat pumps remains not so marked, with a slight advantage of the propane heat pump.



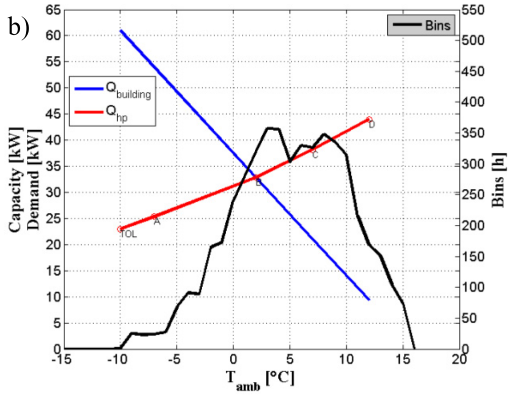


Fig. 5. Heating capacity (red) and heating demand (blue) with the bin hours extracted from UNI EN 14825 regulation. Fan coil case. Strasbourg. (a) Heat pump working with R290. (b) Heat pump working with HFO1234yf.

Table 6. SCOPon and SCOPnet values.

SCOPon	FAN COIL		RAD PANN	
	AVERAGE	COLDER	AVERAGE	COLDER
R290	2.57	2.53	2.96	3.00
R1234yf	2.34	2.23	2.84	2.79

SCOPnet	FAN COIL		RAD PANN	
	AVERAGE	COLDER	AVERAGE	COLDER
R290	3.17	2.73	3.89	3.34
R1234yf	2.80	2.39	3.65	3.10

4. Conclusion

In this work an air to water heat pump working with R290 and HFO1234yf has been modeled and simulated using the software package IMST-ART in order to evaluate the seasonal performance. The characteristic of the compressor and the heat exchanger have been modified in order to obtain the same heating capacity and the same mean ΔT at nominal operative condition. Two different types of applications were considered: fan coils and radiant heat floor panels. Different types of building are considered: apartment block, office and school. The seasonal performance in heating mode, SCOP, is calculated by coupling the performance of the heat pump in different operative conditions to a heating demand curve, in two different climate zones (average and colder). The results of the simulations show better performance of the heat pump with propane in both reference climates and applications. In particular, the major difference in terms of $SCOP_{on}$ is found in the fan coil case at Helsinki, with a gap of 13.5%. Probably it is due to the state of the current technology of the different components. In particular the global performance of the compressor working with R1234yf is not yet optimized at low ambient temperature, i.e. at higher pressure ratio. At the same time a new design of the evaporator is desirable to reduce the pressure drops with R1234yf. The difference of $SCOP_{on}$ between the two heat pumps is lower in radiant heat floor panels case. The maximum gap of $SCOP_{on}$ (7.5%) is found at colder reference climate, where tests conditions required by the European Standard lead to higher pressure ratio and lower performance of the R1234yf heat pump.

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Biography

Francesco Botticella got his MSc in Mechanical Engineering cum laude on 2014. He is a PhD student at the Engineering Department, Sannio University. He is now carrying on studies and experimental campaigns on seasonal performance evaluation of heat pump systems working with low GWP refrigerants.